

The Ultraviolet-Far Infrared Energy Budget of the Gravitationally Lensed Lyman Break Galaxy MS 1512–cB58

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ABSTRACT

A 2-hour service-mode SCUBA observation of the gravitationally-lensed Lyman break galaxy MS 1512–cB58 resulted in a 3σ upper limit of 3.9 mJy at $850\mu\text{m}$. A comparison of this upper limit with values expected from rest-UV/optical measurements of extinction suggests that dust temperature (T_d) and/or emissivity index (β) in cB58 may be substantially higher than is seen in local galaxies, or that the attenuation curve in cB58 may be even gentler than the already quite mild SMC dust law. If dust temperature T_d and emissivity index β in cB58 are similar to those seen in local IRAS-selected galaxies, then cB58's dust mass is $M_d \lesssim 10^{7.7} M_\odot$ and its star formation rate is $\text{SFR} \lesssim 10 M_\odot \text{yr}^{-1}$ (for $q_0=0.1$, $H_0=75 \text{ km s}^{-1} \text{Mpc}^{-1}$). This SFR upper limit is lower than the star formation rate measured from $\text{H}\alpha$, thus giving further support to the notion that (T_d, β) values in cB58 are higher than those seen in local galaxies. It thus appears that our understanding of dust in this extensively studied Lyman break galaxy is poor, and observations at other wavelengths are needed to better understand dust at high redshift. Such observations can be provided by the upcoming SIRTf mission for which cB58's expected flux densities are calculated.

Subject headings: dust, extinction — galaxies: evolution — galaxies: individual (MS 1512–cB58) — galaxies: ISM

1. INTRODUCTION

1.1. Dust in star-forming galaxies at $z \approx 3$

The recent discovery of a large population of $z \approx 3$ star-forming Lyman break galaxies (LBGs; e.g., Steidel et al. 1996, 1999) has generated enormous enthusiasm in the field of galaxy formation and evolution. Among other developments, luminosities of $z \approx 3$ galaxies have been used to trace out the history of cosmic star formation (e.g., Lilly et al. 1996) to a time when the Universe was only $\sim 10\%$ of its present age (e.g., Madau et al. 1996, 1998; Sawicki, Lin, & Yee, 1997; Steidel 1999). At face value, these studies suggest that star formation in the universe rises with lookback

time until flattening or even decreasing sometime after $z \approx 1$. However, this picture of cosmic star formation is complicated by the possibility that substantial amounts of dust may be present in LBGs. Specifically, star formation rates (SFRs) at high redshift are usually inferred from rest-UV luminosities (typically rest-1500Å), but UV light is strongly absorbed by dust. Consequently, if significant dust is present, UV luminosities will be significantly underestimated, resulting in potentially dramatic underestimates of star formation rates.

The amount of dust in LBGs and its effect on the inferred star formation rates remains uncertain. Estimates of absorption in LBGs range between factors of 3 and 20 at rest-1500Å, with a corresponding range of correction factors applied to estimates of star formation rates (e.g., Meurer et al. 1997, 1999; Pettini et al. 1998; Sawicki & Yee 1998). The large range in the estimates of dust attenuation is a result of the different assumptions made regarding both the shape of the underlying spectral energy distributions (SEDs) and, especially, of the dust attenuation laws in Lyman break galaxies. Given the range of possible attenuation corrections that results from reasonable assumptions, it is unlikely that a consensus about the amount of stellar light intercepted by dust will be reached on the basis of rest-frame UV and optical data alone.

A complementary approach to the rest-frame UV-optical studies is that of measuring not the amount of energy absorbed by dust, but the amount re-emitted by it. Because of conservation of energy, these two quantities should be equal, and so observing thermal dust emission in the rest-frame far infrared (FIR) should help constrain the amount of energy absorbed by dust in the rest-frame UV. Thus by observing thermal dust emission one can infer the amount of UV flux absorbed by dust and hence the amount of star formation in high- z galaxies.

The commissioning of the sensitive Submillimetre Common-User Bolometer Array (SCUBA; Holland et al. 1999) on the James Clerk Maxwell Telescope (JCMT) has resulted in a number of what are effectively deep blank-field surveys (e.g., Smail, Ivison, & Blain, 1997; Barger, Cowie, & Sanders 1999; Lilly et al. 1999) as well as two studies which specifically targeted Lyman break galaxies (Ouchi et al. 1999; Chapman et al. 2000). Ouchi et al. (1999) considered the fact that none of the 17 spectroscopically-confirmed LBGs in the northern Hubble Deep Field (HDF) have been detected in an ultra-deep SCUBA image of the HDF (Hughes et al. 1998). Using the SCUBA non-detections together with fits to optical and near-infrared (NIR) photometry, they concluded that LBGs are likely similar to low-reddening starbursts in the local Universe, but that their dust temperature is $T_d \gtrsim 40\text{K}$ (for a dust emissivity index $\beta=1$) — higher than typically found in local galaxies. Chapman et al. (2000) observed a targeted sample of 16 LBGs, but detected only one object. They concluded that predictions from UV colors underestimate LBG 850 μm flux densities by a factor of two or more, except in the case of their sole detection which is associated with an abnormally red and hence, presumably, abnormally dusty outlier. The non-detections of both these studies suggest that typical Lyman break galaxies are beyond the reach of the best sub-mm instrument currently available.

1.2. The gravitationally-lensed Lyman break galaxy MS 1512–cB58

The $z=2.72$ Lyman break galaxy MS 1512–cB58 (cB58 hereafter) was discovered serendipitously behind a rich $z=0.37$ cluster of galaxies (Yee et al. 1996). Gravitational lensing by the cluster potential and by the cluster cD galaxy located only $6''$ away, results in an amplification of cB58’s light by a factor of 22–40 (Seitz et al. 1998), thus making it possible to study cB58 in detail that is impossible for other Lyman break galaxies.

A number of detailed studies of cB58 have been undertaken to date, of which three have addressed the issue of dust: Ellingson et al. (1996) compared rest-UV and -optical photometry of cB58 with spectral synthesis models and concluded that cB58 is dominated by a young stellar population whose light suffers from $E(B-V) \approx 0.3$ of extinction (a factor of ~ 11 at rest-1500 Å) under the assumption of a LMC-like extinction law. Teplitz et al. (2000) compared the observed ratios of Balmer lines with those expected on theoretical grounds, and concluded that attenuation due to dust is $E(B-V) = 0.27$ for a LMC-like attenuation law (a factor of 9 at 1500 Å). Finally, Pettini et al. (2000) used a very deep rest-frame UV spectrum of cB58 in order to study in detail its stellar population; on the basis of the slope of cB58’s UV continuum and the assumption of a relatively young stellar population, they concluded that for an LMC-like extinction law cB58 suffers from a factor of 7 of absorption at rest-1500 Å ($E(B-V) = 0.24$).

While for the same attenuation law the three different estimates of cB58’s extinction agree with each other to better than a factor of two, the picture is complicated by the issue of cB58’s unknown attenuation curve. It is not known what absorption law is appropriate for Lyman break galaxies, yet different local absorption laws can give vastly different results. For example, in the Pettini et al. (2000) study, the LMC-like absorption curve results in a factor of 7 absorption at 1500 Å, an SMC-like curve gives only a factor of 3, while the Calzetti (1997) curve (which is appropriate for local starburst galaxies) gives a factor of 20. Thus, results from the same measurement span a range of a factor of six in attenuation depending on what attenuation curve is assumed. Until the shape of the high redshift attenuation law is better understood, UV-based estimates of extinction in Lyman break galaxies will have to remain uncertain at this level.

As was mentioned in §1.1, complementary insights into the nature of dust at high redshift can be gleaned from observations of the dust’s thermal emission. Gravitational magnification allows cB58 to be observed at rest-frame FIR to a sensitivity unattainable for normal, unlensed, Lyman break galaxies, and so a relatively short (2-hour integration) service-mode observation of cB58 was carried out with SCUBA on the JCMT. This observation, which resulted in a sensitive upper limit on the $850\mu\text{m}$ flux density, is briefly described in §2. In §3 the SCUBA observation is combined with data from the optical and near-IR to produce an overall energy budget for cB58 and to help constrain the nature of its dust. The star formation rate in cB58 and the mass of its dust are constrained in §4, while the detectability of cB58 with the Space InfraRed Telescope Facility (SIRTF) is discussed in §5. The main results are summarized in §6.

2. SCUBA DATA ON cB58

2.1. Data

The galaxy cB58 was observed in service mode with Sub-millimetre Common-User Bolometer Array on the JCMT and a total integration of 7200 seconds was obtained in SCUBA’s photometric mode on 1998 June 26 and 1998 July 2. During observations the instrument was nodded in order to subtract sky and flux calibration was done on both dates by observing Uranus. Atmospheric optical depth values were similar on both dates and the two sets of data were combined after scaling by the gains. The data were reduced by JCMT staff using standard techniques.

No $850\mu\text{m}$ signal was detected at cB58’s location above the 3σ sky noise of 3.9 mJy. This upper limit is of similar sensitivity as, and is in agreement with the 4.2 ± 0.9 mJy value reported recently in a conference paper by van der Werf et al. (2000). Note that because of the presence of a foreground cD galaxy within the SCUBA beam *any* $850\mu\text{m}$ SCUBA observation of cB58 has to be regarded as an upper limit (see § 2.2). Thus, throughout the rest of this paper, 3.9 mJy is adopted as the upper limit on cB58’s $850\mu\text{m}$ flux density.

2.2. Caveats

While the gravitational amplification provided by the foreground cluster and its cD galaxy make it possible to reach deep sensitivity limits in moderate amounts of observing time, they also introduce two complications which need to be noted.

The first complication is that for further analysis it is necessary to assume that the gravitational amplification is the same for the optical/NIR and for sub-mm light. This assumption is reasonable given that the young stars which are responsible for the rest-UV light are likely well mixed on galactic scales with the dust which is responsible for absorbing their UV light and re-emitting it in the FIR. However, were this not the case, then the assumption that the sub-mm flux is amplified by the same factor as the rest-UV and -optical light would not be true and would complicate the comparison of optical and sub-mm fluxes presented in §3; it would also put in doubt the calculations of FIR limits on the star formation rate and dust mass in cB58 (§4), as these calculations assume that the gravitational amplification of cB58’s sub-mm light can be estimated from the optical.

The second complication is introduced by the presence $6''$ away of the cD galaxy in the centre of the cluster MS1512. This foreground object is within the $15''$ diffraction-limited beam of the JCMT at $850\mu\text{m}$ and — given that cD galaxies at $z \sim 0.4$ can produce appreciable sub-mm emission (e.g., Edge et al. 1999) — may be contributing to the $850\mu\text{m}$ flux density. Therefore it should be kept in mind that *any* SCUBA observation of cB58 — even one which reports a detection, such as that by van der Werf et al. (2000) — has to be regarded as an upper limit on that object’s flux density. Throughout the analysis that follows, it will be assumed that the upper limit on cB58’s $850\mu\text{m}$ flux density is 3.9 mJy. This assumption is conservative in that it is consistent with both

the non-detection reported above and with the van der Werf et al. (2000) value, and does take into account any possible contributions from the neighbouring cD galaxy.

3. THE UV-FIR ENERGY BUDGET OF cB-58

In this Section, the 3.9 mJy upper limit on cB58’s 850 μ m flux density will be compared with expectations based on observations of the rest-UV and -optical regions of its SED. The comparison will be done in terms of observed quantities — fluxes and flux densities, rather than luminosities and luminosity densities — thereby avoiding the need to assume a specific cosmology and lensing magnification. In §3.1, recent UV-based measurements of extinction in cB58 will be used to estimate the amount of rest-UV flux that is absorbed by dust. Then (in §3.2) the expected 850 μ m flux density will be calculated using the assumption that all the flux absorbed at rest-UV is re-radiated in the rest-FIR as a modified blackbody. In §3.3 this expected 850 μ m flux density will be compared with the 3.9 mJy SCUBA upper limit to constrain the properties of dust in cB58.

3.1. Flux absorbed by dust in the rest-UV

To estimate cB58’s expected sub-mm flux density, $S_{850\mu m}$, it is first necessary to calculate F_{abs} , the amount of flux that is absorbed at rest-frame UV and optical wavelengths. The calculation of F_{abs} was done by comparing the dust-free and dust-attenuated model SEDs of young stellar populations (1996 version of the Bruzual & Charlot 1993 models) after normalizing them to cB58’s broadband photometry (Yee et al., 1996; Ellingson et al., 1996). Symbolically this calculation can be expressed as

$$F_{abs} = n \int_0^\infty [f_\lambda(\lambda) - a(\lambda)f_\lambda(\lambda)]d\lambda, \quad (1)$$

where f_λ is the unattenuated SED, $a(\lambda)$ is the extinction as a function of wavelength for the assumed $E(B-V)$ value and extinction curve, and n is the normalization obtained by scaling the attenuated SED to the broadband photometry (see also Fig. 1).

The specific values of the various parameters, such as the amount of extinction, age of the stellar population, metallicity, and stellar initial mass function, were as follows (see also Table 1). Three extinction laws were considered — the SMC law of Bouchet et al. (1985), the Fitzpatrick (1986) LMC law, and the Calzetti (1997) law appropriate for local starburst galaxies. $E(B-V)$ values were taken from Pettini et al. (2000), and are $E(B-V)=0.1$ for the SMC law, $E(B-V)=0.24$ for the LMC law, and $E(B-V)=0.29$ for the Calzetti law; the Pettini et al. (2000) values were adopted as of the three extinction measurements for cB58 (Ellingson et al. 1996; Pettini et al. 2000; Teplitz et al. 2000) they give the lowest extinction corrections and are thus the most conservative (§ 1.2). The underlying SEDs were assumed to be dominated by young stellar populations since the UV-optical light in cB58 is dominated by young stars (Ellingson et al. 1996, Pettini et al. 2000);

specifically, models with ages of 10, 100, and 255 Myr were used. Both instantaneous burst models and constant SFR models were initially considered, but it was found that for the 100 and 255 Myr instantaneous burst models the fit between the model SED and the broadband photometry was extremely poor and so for the instantaneous burst case only the 10 Myr model was retained. Different metallicities and initial mass functions (IMFs) were considered at first, but it was found that F_{abs} does not depend strongly on either metallicity or IMF; for definitiveness, metallicity was taken to be $0.4Z_{\odot}$ and the Salpeter (1955) IMF was adopted.

As can be seen in Table 1, the values of F_{abs} for the Calzetti attenuation law cluster around $F_{abs} = 2.5 \cdot 10^{-15} \text{Wm}^{-2}$, those for the LMC law are around $1.0 \cdot 10^{-15} \text{Wm}^{-2}$, and those for the SMC law are typically around or slightly above $0.5 \cdot 10^{-15} \text{Wm}^{-2}$. Motivated by these typical F_{abs} values, let us define three cases for dust attenuation, namely “case C”, corresponding $F_{abs} = 2.5 \cdot 10^{-15} \text{Wm}^{-2}$, “case L”, corresponding $F_{abs} = 1.0 \cdot 10^{-15} \text{Wm}^{-2}$, “case S”, corresponding $F_{abs} = 0.5 \cdot 10^{-15} \text{Wm}^{-2}$ (see bottom of Table 1). These three cases correspond broadly to the effects of the three different attenuation laws.

3.2. Expected 850 μm flux density

With the estimate of F_{abs} in hand, the expected flux density at 850 μm can be calculated by assuming conservation of energy ($F_{abs} = F_{em}$) and a dust emissivity curve. Specifically, let’s assume that the dust radiates as an optically thin modified blackbody, $\{1 - \exp[-(\nu/\nu_0)^{\beta}]\}B_{\nu}(T_d)$, where B_{ν} is the Planck function and $\nu_0 = c/\lambda_0$ is the critical frequency at which dust becomes optically thin. The emitted flux is then the integral of the redshifted emissivity curve,

$$F_{em} = n' \int_0^{\infty} \{1 - \exp[-(\nu/\nu_0)^{\beta}]\} B_{\nu/(1+z)}(T_d) d\nu, \quad (2)$$

where n' is the constant of proportionality which incorporates cosmological terms and which is evaluated by requiring that $F_{em} = F_{abs}$. The expected 850 μm flux density is then

$$S_{\nu}(850\mu\text{m}) = n' \{1 - \exp[-(\nu(850\mu\text{m})/\nu_0)^{\beta}]\} B_{\nu/(1+z)}^{850\mu\text{m}}(T_d), \quad (3)$$

where the redshifted modified blackbody is evaluated at the observed wavelength of 850 μm .

Figure 2 shows the expected values of 850 μm flux density for case S dust attenuation (i.e., for $F_{abs} = 0.5 \cdot 10^{-15} \text{Wm}^{-2}$) and under the assumption that dust is optically thin everywhere ($\nu_0 \rightarrow \infty$, or $\lambda_0 \rightarrow 0$). Note that for any given $S_{\nu}(850\mu\text{m})$ value, dust temperature and emissivity index are degenerate, so it would be impossible to separate T_d from β even if a SCUBA 850 μm detection were available. For a SCUBA *upper limit*, it is only possible to rule out *areas* of (T_d, β) parameter space: for a given upper limit value, the area to the right of the corresponding curve is permitted whereas that to its left is ruled out.

3.3. Comparison of cB58 to galaxies in the local Universe

Figure 3 shows the constraints in the (T_d, β) plane imposed by the SCUBA 3.9 mJy upper limit for different assumptions about dust absorption and emission laws. Specifically, areas to the upper right of the *solid curves* are the values of T_d and β allowed in the case of dust emission that is optically thin everywhere ($\lambda_0 \rightarrow 0$). Labels on the curves indicate case L, S, and C dust, while open circles show values of (T_d, β) measured by Dunne et al. (2000) for 104 local galaxies from the IRAS Bright Galaxy Sample (Soifer et al. 1989). The restrictions on the (T_d, β) parameter space become more severe when $\lambda_0 > 0$, as is illustrated for $\lambda_0 = 125 \mu\text{m}$ (*broken lines*).

No galaxy from the local, IRAS-selected sample of Dunne et al. (2000) can match the (T_d, β) values required of cB58 for any of the dust absorption cases (C, L, S) and λ_0 values. The discrepancy is least severe when dust emission is assumed to be optically thin everywhere ($\lambda_0 \rightarrow 0$) and becomes worse for the more realistic case of $\lambda_0 > 0$. Furthermore, the discrepancy is strongest for case C dust, which corresponds to the Calzetti extinction curve which is derived for starburst galaxies and could thus be thought to be the most appropriate extinction curve for cB58. Thus, for all the absorption laws considered here, the optical-NIR data require so much flux to be absorbed in the rest-frame UV that it cannot be re-emitted in the rest-FIR at dust temperatures and β values typical of galaxies in the local universe (see also van der Werf et al. 2000).

A number of possibilities exists which may account for this apparent disagreement between the (T_d, β) values required of cB58 and those seen in local galaxies:

1. It is possible that dust in cB58 is indeed hotter than dust seen in local IRAS selected galaxies. A similar conclusion was reached for Hubble Deep Field LBGs by Ouchi et al. (1999), who concluded that their dust temperatures are $T_d \gtrsim 40\text{K}$ under the less robust assumption of a Calzetti attenuation curve. The discrepancy in dust temperature between cB58 and local galaxies may be due to evolution in dust properties between $z \approx 3$ and today. Alternatively, it could be that cB58 is a very L_{FIR} -luminous member of a continuum of galaxies whose less luminous members have more normal dust temperatures.
2. An alternative is that a significant component of *hot* dust is present in cB58. No attempt has been made here to fit a two-temperature dust model because to do so data at multiple sub-mm wavelengths would be needed. However, if significant amount of the overall FIR flux is radiated via a hot dust component then the $850 \mu\text{m}$ flux density would be lower than predicted with the simple single-temperature models of §3.2. Indeed, Ouchi et al. (1999) estimate that in some local galaxies as much as a third of the overall FIR flux may be radiated by hot dust. However, the discrepancy between the SCUBA limit for cB58 and local galaxies is generally larger than a factor of 2 — only in the most favourable case S optically thin dust could the $850 \mu\text{m}$ SCUBA limit be reconciled with *some* members of the local galaxy population and even then only with one or two outliers in the 104 galaxies in the Dunne et al. (2000) sample. It is thus unlikely that the presence of a hot dust component can account for the

entire discrepancy, unless substantially more flux is radiated by hot dust than by cold dust, in which case we revert to the the conclusion in item (1) above.

3. A third possibility is that β is substantially higher than in local galaxies. It is possible to have T_d similar to those observed in local galaxies (see Fig. 3) provided $\beta \gtrsim 2.5$. While such high β values are not seen in local galaxies, it is possible that dust at high redshift has unusual composition which might result in such a high emissivity index.
4. Another possibility is that the attenuation laws (SMC, LMC, Calzetti) used in §3.1 to compute F_{abs} are inappropriate for cB58. If the attenuation curve in cB58 were more mild than even the SMC law, then the expected flux densities would be overestimated. A milder extinction curve could restore agreement between (T_d, β) in cB58 and in the local sample. However, if such a mild attenuation curve is required in Lyman break galaxies, then even the lowest, factor-of-3, estimates of the effect of dust on star formation rates in LBGs and on the cosmic star formation rate density at high redshift would have to be revised *downwards*.
5. The final possibility considered is that at least some of the sub-mm flux comes from a different region of cB58 than the optical light. If this were the case then one might expect the sub-mm and optical fluxes to be uncorrelated, especially so if lensing amplified the two components by different factors. However, given that there is already a *deficit* of rest-FIR light, any *additional* FIR-emitting component would only make the discrepancy worse. Alternatively, it is also extremely improbable that the dust which absorbs the rest-UV radiation is lensed more strongly than the dust which re-emits it. Thus the deficit seen in the sub-mm cannot be explained as due to emission from a component which is different from that responsible for absorption in the UV.

It thus appears that dust in cB58 cannot be easily modeled by a simple model of attenuation and single-temperature emission unless one assumes (T_d, β) values vastly different from those seen in local galaxies, or a very mild dust attenuation law. Data at other FIR wavelengths are needed to better constrain the shape of the dust emission curve and hence the properties of dust in cB58. Possibilities for obtaining such data in the near future are briefly explored in §5. However, first the analysis of the data already in hand will be completed by calculating the SCUBA limits on cB58's star formation rate and mass of dust.

4. LIMITS ON STAR FORMATION RATE AND DUST MASS

Assuming that the sub-mm continuum in cB58 is due to thermal emission from single-temperature dust heated by massive young stars, the 3.9 mJy upper limit on the $850\mu\text{m}$ flux density can be used to constrain both the star formation rate and the mass of dust in that galaxy.

4.1. Star formation rate

The star formation rate of cB58 can be constrained using the limit on the $850\mu\text{m}$ flux density. Following Hughes et al. (1997):

$$SFR = \frac{1}{f_{lens}} \epsilon 10^{-10} \frac{L_{FIR}}{L_{\odot}} M_{\odot} \text{yr}^{-1}, \quad (4)$$

where it is assumed that the lensing magnification of cB58's flux is $f_{lens} = 30$ (Seitz et al. 1998 give the allowable range of 22–40). Hughes et al. 1997 give $\epsilon=0.8\text{--}2.1$, and here the value of $\epsilon=2.1$ is adopted because using this high value will give a conservative, robust upper limit on the star formation rate. The far-IR luminosity, L_{FIR} , is calculated by integrating the modified blackbody in the observed frame,

$$L_{FIR} = 4\pi D_L^2 \int_{(1+z)10\mu m}^{(1+z)2mm} [\nu/(1+z)]^{\beta} B_{\nu/(1+z)}(T_d) d\nu, \quad (5)$$

and normalizing using the constraint that the $850\mu\text{m}$ flux density is <3.9 mJy. Here, D_L is the usual luminosity distance, given by

$$D_L = \frac{2c}{H_0 \Omega_0^2} [\Omega_0 z + (\Omega_0 - z)(\sqrt{\Omega_0 z + 1} - 1)]. \quad (6)$$

Note that the calculation of L_{FIR} (Eq. 5) depends on the dust temperature and emissivity index β and that, therefore, the constraint on the SFR will depend on the assumed values of these (unknown) parameters. Note also that because Eq. (5) is normalized using an upper limit on the $850\mu\text{m}$ flux density, the calculated SFR will also be an upper limit.

Figure 4 shows the constraints on cB58's star formation rate as a function of dust temperature T_d and emissivity index β and for an assumed cosmology of $q_0 = 0.1$ and $H_0 = 75 \text{ km s}^{-1} \text{Mpc}^{-1}$. If cB58 were comparable to a typical local IRAS-selected galaxy then it would have $T_d=36\text{K}$ and $\beta=1.3$ (mean values for the sample of Dunne et al., 2000) and would thus have a star formation rate of $\lesssim 10 M_{\odot} \text{yr}^{-1}$. This upper limit on the star formation rate is lower than the (lensing-corrected) value of $21 M_{\odot} \text{yr}^{-1}$ derived by Teplitz et al. (2000) from cB58's $\text{H}\alpha$ flux. Indeed, to be consistent with the Teplitz et al. $\text{SFR}_{\text{H}\alpha}$ value, cB58 must be located to the upper right of the $< 21 M_{\odot}/\text{yr}$ line in Fig. 4 — i.e. at (T_d, β) values higher than those seen in typical local galaxies. Note that this argument, which is based on comparing the $\text{H}\alpha$ -based SFR with the SCUBA upper limit on the $850\mu\text{m}$ flux density, is independent of the argument based on the comparison of rest-UV extinction models with the SCUBA limit (§3) and yet results in the same conclusion that the (T_d, β) values in cB58 are high and unlike those seen in local galaxies. It thus strengthens the conclusion of §3.3 that dust in cB58 appears to be unlike that in local IRAS-selected galaxies.

4.2. Mass of dust

As with the star formation rate, the mass of dust can be constrained using the limit on the 850 μ m flux density. Following Hughes et al. (1997), the mass of dust can be expressed as

$$M_d = \frac{1}{f_{lens}} \frac{S^{obs} D_L^2}{(1+z) k_d^{rest} B(\nu^{rest}, T_d)}, \quad (7)$$

where S^{obs} is the constraint on the 850 μ m flux density (i.e., $S^{obs} < 3.9$ mJy), $z = 2.72$ is the redshift of cB58, and $B(\nu^{rest}, T_d)$ is the value of the Planck function evaluated at the rest frequency which corresponds to the observed wavelength of 850 μ m. The mass absorption coefficient k_d^{rest} is quite uncertain, with different estimates of $k_d^{rest}(800\mu\text{m})$ ranging from 0.04 m²kg⁻¹ to 0.3 m²kg⁻¹ (Hughes et al. 1997); here, $k_d^{rest}(800\mu\text{m})=0.04$ is adopted, since this low k_d^{rest} gives a conservative, robust upper limit on M_d . To extrapolate $k_d^{rest}(800\mu\text{m})$ to the observed rest-wavelength of 850/(1+z) μ m, it is assumed that $k_d^{rest} \propto \lambda^{-\beta}$.

Figure 5 shows the limits on cB58’s dust mass for a range of values of temperature and β and for a $q_0=0.1$, $H_0=75$ km s⁻¹Mpc⁻¹ cosmology. Assuming that (T_d, β) values in cB58 are similar to the mean of the local sample of Dunne et al. (2000), the mass of dust in cB58 is $M_d \lesssim 10^{7.7} M_\odot$. If, on the other hand, it is assumed that (T_d, β) values in cB58 are higher than is seen in local IRAS-selected galaxies, then the upper limit on the dust mass drops somewhat to, for example, $M_d \lesssim 10^{7.3} M_\odot$, for $(T_d, \beta)=(60\text{K}, 1.3)$.

5. PROSPECTS FOR THE (NEARBY) FUTURE

As was discussed in §3.3 and §4.1, dust properties in cB58 appear to be different from those seen in local IRAS-selected galaxies. To constrain the shape of cB58’s dust emissivity curve, observations at additional rest-frame FIR wavelengths are needed. Such observations will be possible with the Space Infrared Telescope Facility (SIRTF) which is scheduled for launch in mid-2002. Figure 6 shows the flux densities expected in the 70 μ m and 160 μ m SIRTf bandpasses from case S optically thin dust. The area to the upper right of the dotted curve is the region allowable by the comparison of optical-NIR and SCUBA data. Thus, the thermal dust contribution to the 70 μ m flux density is likely to be $\gtrsim 0.5$ mJy, which is attainable at 5σ in ~ 4 hours of integration¹. Unless T_d is above 100K, cB58 can be expected to have a flux density of $\gtrsim 10$ mJy at 160 μ m, which will be detectable to very high significance in only a few minutes of SIRTf time. Therefore, cB58 should be easily detectable with SIRTf at both 70 μ m and 160 μ m. Such multiwavelength FIR observations will help constrain the shape of the emissivity curve in cB58, and will thus yield important insights into the properties of dust in this prototypical Lyman break galaxy and, by extension, into the true amount of star formation at $z \approx 3$.

¹SIRTf sensitivities are taken from http://sirtf.caltech.edu/SciUser/MIPS/html/mipspt_sens.html

6. CONCLUSIONS

A 2-hour SCUBA observation of the Lyman break galaxy MS 1512–cB58 yielded a 3σ upper limit of 3.9 mJy at $850\mu\text{m}$. Given that cB58 is gravitationally lensed by a factor of ~ 30 , it is thus not surprising that virtually no other Lyman break galaxies have been detected in the sub-millimeter even in very deep surveys (Hughes et al. 1998; Chapman et al. 2000).

The SCUBA upper limit on cB58’s $850\mu\text{m}$ flux density is surprisingly low when compared with values expected on the basis of rest-frame UV/optical observations (§3). This discrepancy suggests that values of dust temperature and/or emissivity index β may be substantially higher in cB58 than in local IRAS-selected galaxies. Alternatively, the attenuation curve in cB58 may be gentler even than the quite mild SMC dust law, resulting in substantially less absorption in the rest-UV (factor of $\lesssim 3$ at 1500\AA) than is commonly assumed (Pettini et al. 2000; Teplitz et al. 2000). In either case, it is clear that the understanding of dust in this extensively studied Lyman break galaxy is poor.

The SCUBA upper limit constrains the mass of dust in cB58 to $M_d \lesssim 10^{7.7} M_\odot$ for a $q_0=0.1$, $H_0=75$ km/s/Mpc cosmology and a lensing magnification of $f_{lens}=30$ (§4.2). If (T_d, β) values similar to those seen in local galaxies are adopted for cB58, then its star formation rate is $\text{SFR} \lesssim 10 M_\odot \text{yr}^{-1}$ (§4.1). This upper limit on cB58’s star formation rate is lower than the star formation rate measured from $\text{H}\alpha$ by Teplitz et al. (2000) and thus gives further support to the notion that (T_d, β) values in cB58 are higher than those in local galaxies.

This analysis illustrates that properties of dust in Lyman break galaxies are not well understood. Further multiwavelength studies will be needed to understand the shape of the dust emissivity curve in cB58 and in other LBGs. Estimating the flux emitted by dust in cB58 from that absorbed in the rest-frame UV, it is found that cB58 should be easily detectable at $70\mu\text{m}$ with SIRTf, and — with a few hours’ integration — at $160\mu\text{m}$. Using such multiwavelength studies to compare the picture of dust in absorption with that of dust in emission may eventually lead to an understanding of dust in Lyman break galaxies that is lacking at present.

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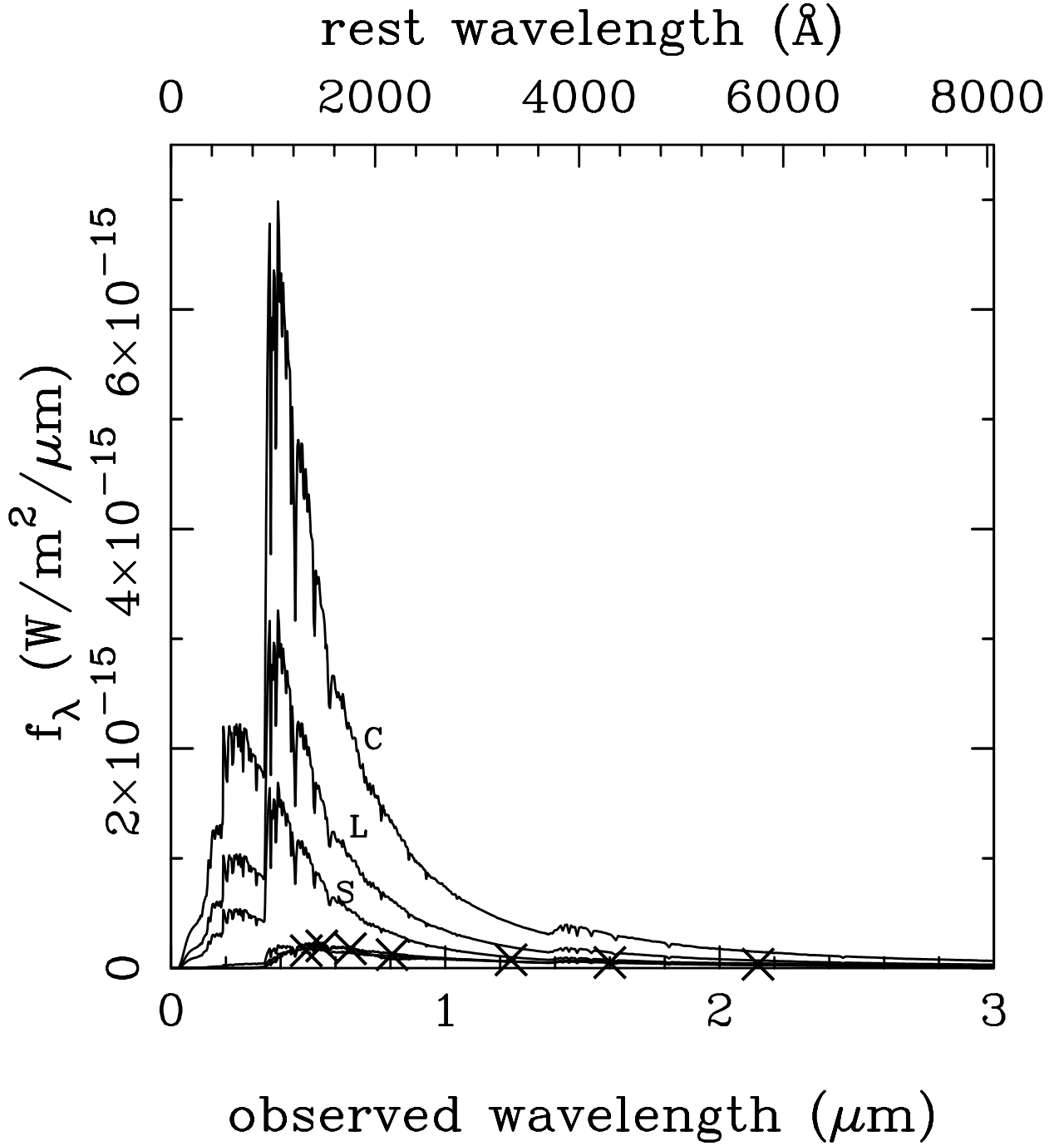


Fig. 1.— Attenuated and unattenuated SED curves for cB58. Crosses show the optical and IR photometry of cB58 from Yee et al. (1996) and Ellingson et al. (1996). The curves that pass through the crosses are Bruzual and Charlot (1993) models adjusted for dust attenuation using the Calzetti (1997), LMC, and SMC extinction laws with extinction values from Pettini et al. (2000), while the three upper curves, labelled “C”, “L”, and “S”, are the same Bruzual & Charlot models but uncorrected for extinction. Areas between the upper, unattenuated, curves, and the corresponding lower, attenuated ones, are the amounts of flux absorbed by dust (see Eq. 1).

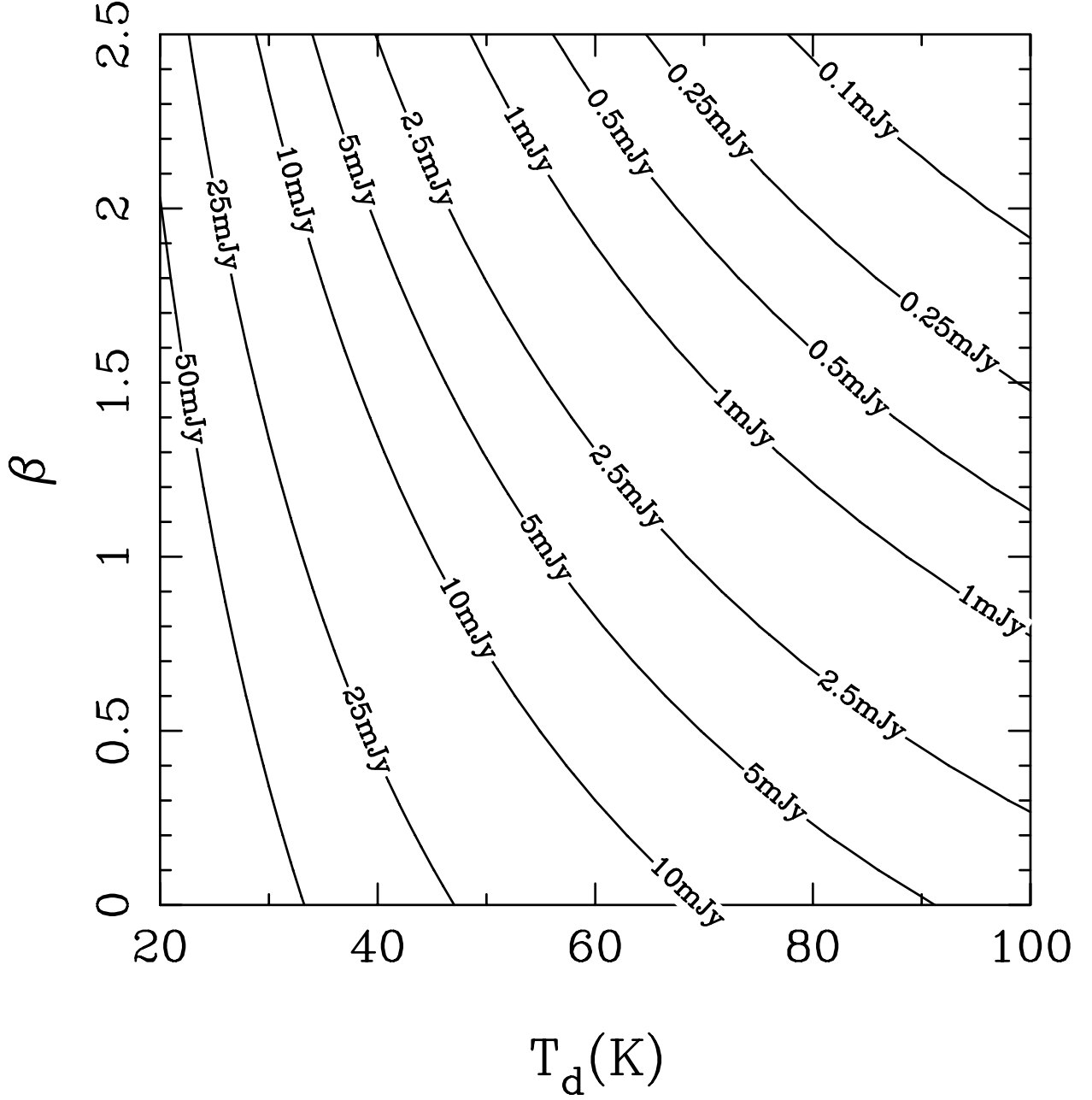


Fig. 2.— Expected $850\mu\text{m}$ flux density for the illustrative case of SMC-like attenuation (“case S”) that is optically thin everywhere in the FIR. Note that since the normalization of Eq. (3) depends on the rest-UV absorption only through the value of F_{abs} , the $S_{\nu(850\mu\text{m})}$ values for cases L and C can easily be read off from the Figure by multiplying the plotted flux density values by 2 (for case L) or 5 (for case C).

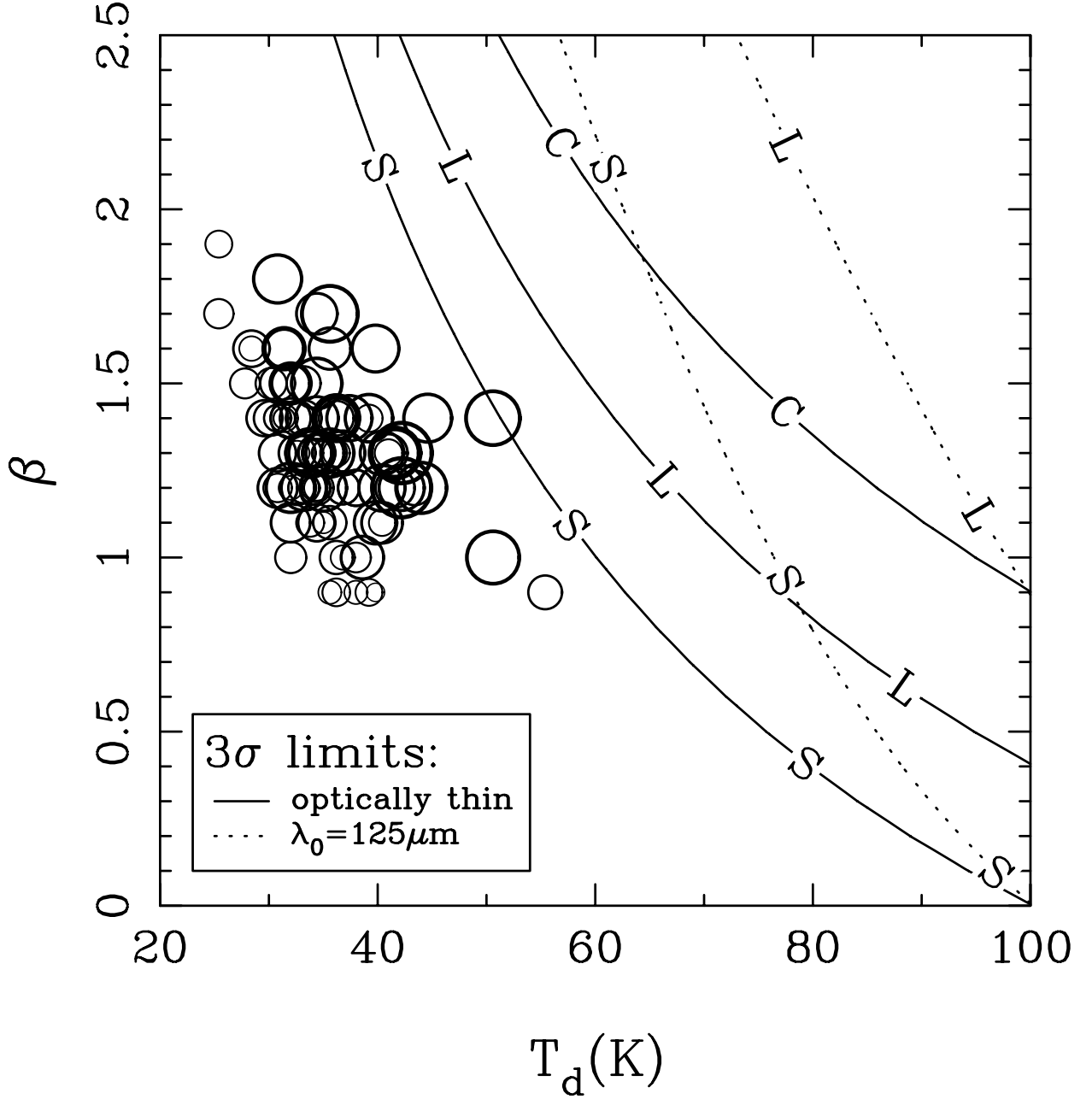


Fig. 3.— Regions in $T_d - \beta$ space allowed by the combination of SCUBA $850\mu\text{m}$ upper limit and rest-frame UV/optical data. The solid and broken lines show the 3σ upper limits, with the allowable regions being to the upper right of each curve. The solid curves are for dust that is optically thin at all wavelengths, while the broken curves are for dust that becomes optically thick at $\lambda_0=125\mu\text{m}$. The curves labelled “S” are for the case of SMC-like extinction in the UV (see Table 1 for the definition), those labelled “L” are for LMC-like dust, and those labelled “C” are for Calzetti-like dust. Open circles represent local galaxies from the survey of Dunne et al. (2000), with symbol size proportional to FIR luminosity. Note that the local galaxies lie outside the regions permitted for cB58, suggesting that dust properties in cB58 are unlike those in the local sample.

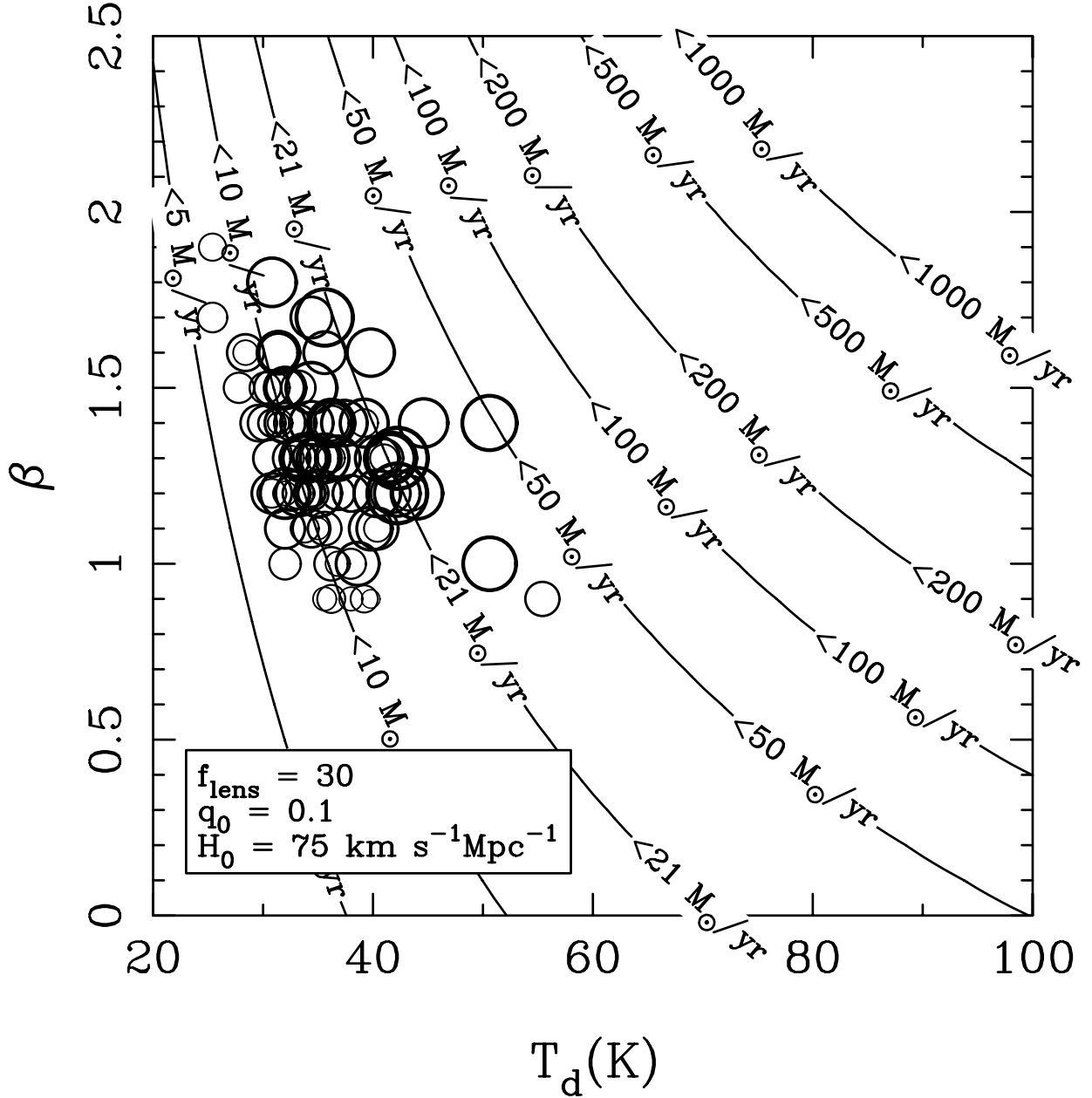


Fig. 4.— Sub-mm limits on the star formation rate in cB58. 3σ upper limits for the adopted cosmology and lensing magnification are shown as a function of dust temperature T_d and emissivity index β . To be consistent with the Teplitz et al. (2000) $\text{SFR}_{H\alpha}$, cB58’s (T_d, β) values must be to the upper right of the $<21 M_{\odot}/\text{yr}$ line, and are thus consistent with only a few of the 104 local galaxies in the sample of Dunne et al. (2000).

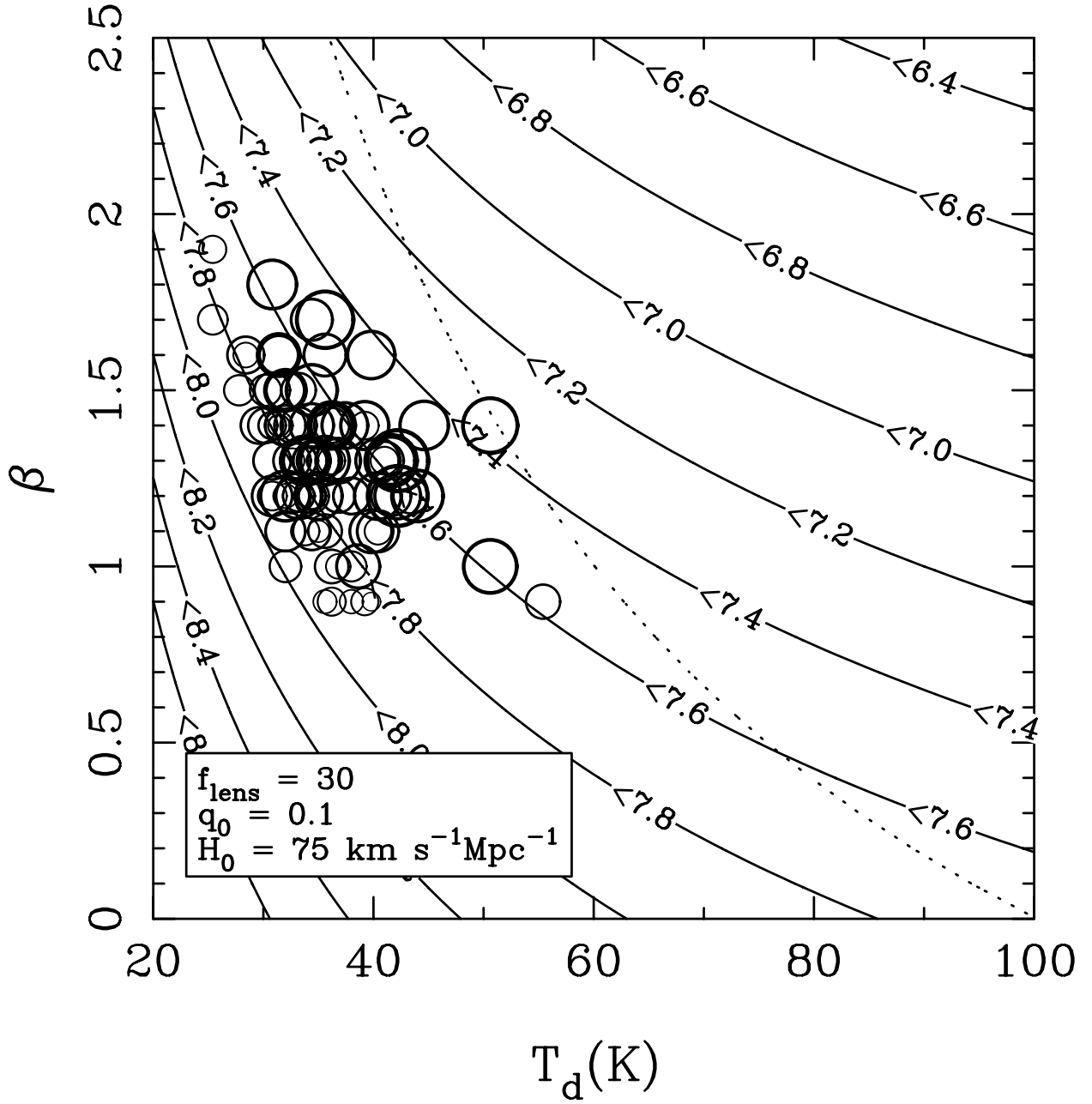


Fig. 5.— Limits on the mass of dust. The solid lines, labelled in units of $\log(M_d/M_\odot)$, indicate the 3σ limits on the mass of dust for the adopted cosmology and lensing magnification. The area of (T_d, β) space to the right of the broken line is allowed by the (least restrictive) case S optically thin dust.

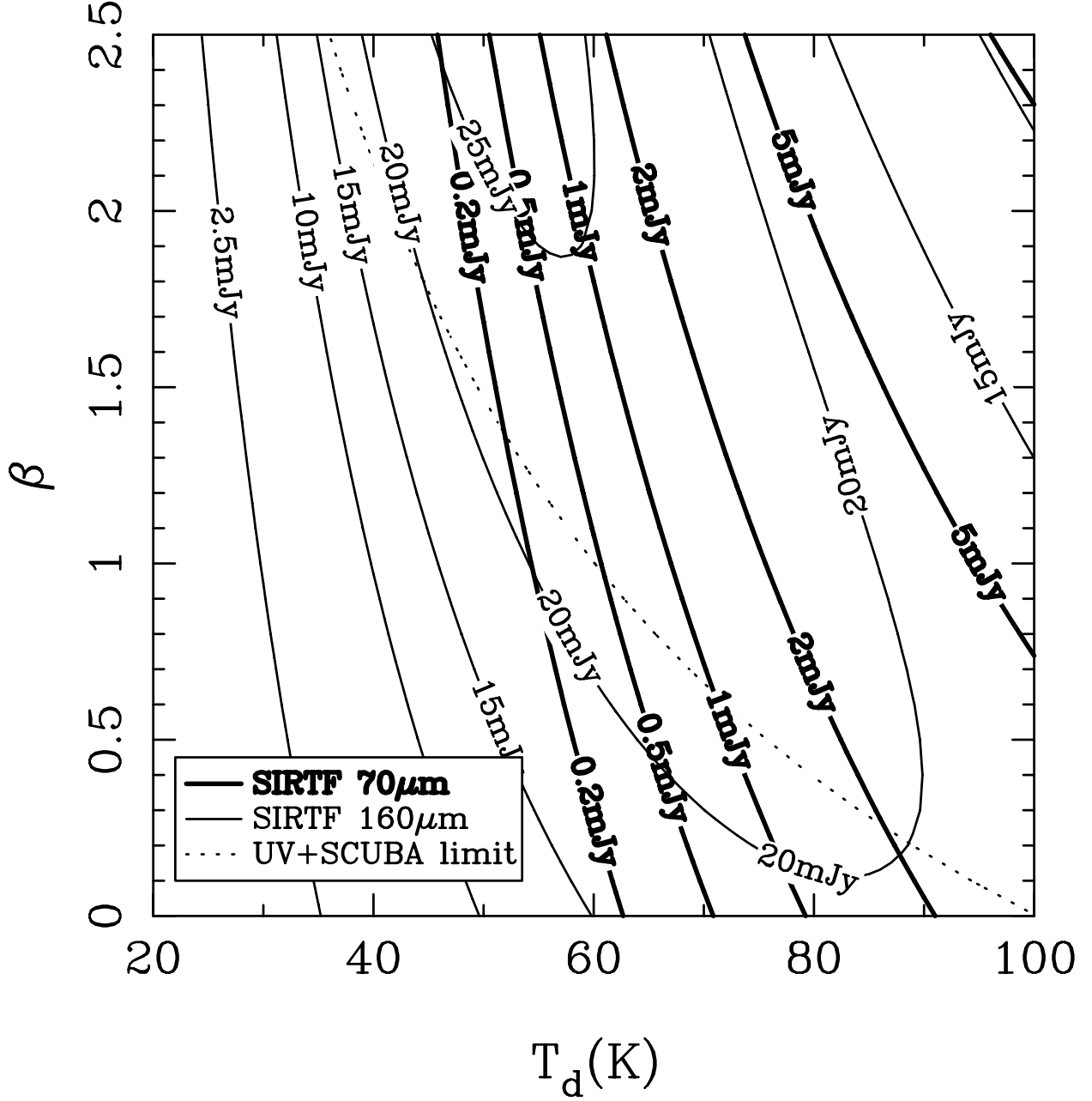


Fig. 6.— Expected flux densities in the SIRTf 70 μ m and 160 μ m bands, for case S, optically thin dust. The area to the upper right of the dotted line is the region allowable by the UV-FIR constraints in the case of the (least restrictive) optically thin case S dust. Flux density values for cases L and C dust can be easily read off from this figure by multiplying the flux density values plotted by 2 and 5, respectively.

Table 1. Flux absorbed by dust for different SED models and dust laws

Dust	history ^a	age ^b (Myr)	F_{abs} (10^{-15}Wm^{-2})
SMC, $E(B-V)=0.10$	ssp	10	0.5
	cons	10	0.8
	cons	100	0.6
	cons	255	0.5
LMC, $E(B-V)=0.24$	ssp	10	0.9
	cons	10	1.3
	cons	100	1.0
	cons	255	0.9
Calzetti, $E(B-V)=0.29$	ssp	10	2.1
	cons	10	3.2
	cons	100	2.4
	cons	255	2.0
Case S			0.5
Case L			1.0
Case C			2.5

^aHistory of star formation. Following Bruzual & Charlot (1993), cons refers to a constant star formation history and ssp refers to an instantaneous burst of star formation

^bAge since the onset of the episode of star formation that dominates the optical-IR SED.